COMMENT ON THE KAMIOKANDE ATMOSPHERIC NEUTRINO DEFICIT [1]

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Abstract

I describe an attempt to understand the significance of the atmospheric neutrino deficit observed by the Kamiokande neutrino detector. In particular, I am concerned with the statistical significance quoted for the zenith-angle dependence of the deficit, which has been cited as evidence for neutrino flavor oscillations free of systematic uncertainties.

The Kamiokande neutrino detector collaboration has measured the flux of electron neutrinos and muon neutrinos produced in cosmic-ray showers in the Earth's atmosphere [1]. They observe a deficit in the flux of muon neutrinos ("μ-like events") relative to the flux of electron neutrinos ("e-like events") for neutrinos with energies above about 1.3 GeV. The Kamiokande collaboration presents two pieces of evidence that their data are inconsistent with standard-model neutrinos without flavor oscillations. First, the ratio of total number of μ-like to total number of e-like events, $(\mu/e)_{\mathrm{Data}}$, divided by the expected ratio, $(\mu/e)_{\mathrm{MC}}$, is inconsistent with unity. Second, they observe an angular dependence of this "ratio of ratios", $(\mu/e)_{\mathrm{Data}}/(\mu/e)_{\mathrm{MC}}$. The latter effect, if significant, would be more suggestive, if not compelling, since it would demonstrate a direct dependence on the distance to the cosmic ray shower producing the neutrinos that is free of systematic uncertainties. Presumably, the oscillations of muon neutrinos into another type of neutrino over distances characteristic of the Earth's radius are being observed.

The data are summarized in Figures 3 and 4 of Reference [1]. Figure 3 shows the absolute rate of e-like and μ-like events binned by zenith angle. Figure 4 shows the "ratio of ratios" with the same binning. Although the uncertainties are all approximately the same size in the raw data presented in Figure 3, the uncertainties vary significantly from bin to bin in Figure 4. Examining the numbers shows that the Kamiokande group has propagated uncertainties estimated from the data points themselves to arrive at the uncertainty on each point in Figure 4. As a result points which might be low merely due to a fluctuation, will have uncertainty estimates that are too low. While such estimates for the uncertainties may be the best available for data for which there is no model, they are inappropriate for data which are subsequently compared to a particular hypothesis. For testing a hypothesis, one would prefer to use uncertainties based on the *expected* rather than *observed* rates.

In this reanalysis, the raw count rates are used directly to test if the atmospheric neutrino deficit has a zenith-angle dependence inconsistent with any flat distribution. A fit is

[1] This manuscript is the result of an observation I made publicly at the *XXXth Rencontres de Moriond*, March 12-18, 1995.

performed to minimize the χ^2 recommended [2] for rates following a Poisson distribution:

$$\chi^2 = \sum_{\ell=e,\mu} \sum_{i=1}^{5} [2(N_i^{\rm exp} - N_i^{\rm obs}) \ + \ 2N_i^{\rm obs} \ln(N_i^{\rm obs}/N_i^{\rm exp})], \tag{1}$$

where the sums are over the five bins in both the electron- and muon-neutrino distributions and the $N_i^{\rm exp}$ are given by:

$$\begin{aligned} N_i^{\rm exp}(e) &= \alpha \ N_i^{\rm exp-SM}(e) \\ N_i^{\rm exp}(\mu) &= \alpha\beta N_i^{\rm exp-SM}(\mu). \end{aligned}$$

The parameters α and β are chosen to minimize χ^2. The parameter α absorbs an overall normalization; the parameter β is the correction factor to the "ratio of ratios" sought by Kamiokande.

The fit to the Kamiokande data yields $\beta = 0.56^{+0.08}_{-0.07}$(stat.), in good agreement with the Kamiokande result of $0.57^{+0.08}_{-0.07}$(stat.), from a different method. The calculated χ^2/d.o.f. is 15.4/8=1.93. The corresponding confidence level with which a flat distribution is excluded by the data is 94.8%. This is less than the "conservative" 99% claimed in the Kamiokande paper and much less than the confidence level conventionally required to claim a signal. As a check, the same fits are done to 5000 Monte Carlo experiments. The returned values of α and β follow the expected distributions. The number of experiments with $\chi^2 > 15.4$ is 5.8%, in agreement with the extracted 94.8% confidence level.

In conclusion, the observed deviation of the Kamiokande "ratio of ratios" from flatness is expected in 1 in 20 such experiments. It is noted that the uncertainties on the data points in Figure 4 of Reference [1] are misleading.

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[1] Y. Fukuda *et al.*, Phys. Lett. **B335** (1994) 237.
[2] S. Baker and R. D. Cousins, Nucl. Instr. and Meth., **221** (1984) 437.